



Development and application of a modeling approach for surface water and groundwater interaction

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ABSTRACT

Investigation of the interaction of surface water (SW) and groundwater (GW) is critical in order to determine the effects of best management practices (BMPs) on the entire system of water resources. The objective of this research was to develop a modeling system for considering SW–GW interactions and to demonstrate the applicability of the developed system. A linked modeling approach was selected to consider SW–GW interaction. The dual-simulation scheme was developed to consider different time scales between a newly developed surface model: Dynamic Agricultural Non-point Source Assessment Tool (DANSAT), and existing groundwater models; a three-dimensional finite-difference groundwater flow model (MODFLOW) and a modular three-dimensional transport model (MT3D). A distributed and physically based DANSAT predicts the movement of water and pesticides in runoff and in leachate at a watershed scale. MODFLOW and MT3D simulate groundwater and pesticide movement in the saturated zone. Only the hydrology component of the linked system was evaluated on the QN2 subwatershed in the Nomini Creek watershed located in the Coastal Plain of Virginia mainly due to lack of observed data for MT3D calibration. The same spatial scale was used for both surface and groundwater models while different time scales were used because surface runoff occurs more quickly than groundwater flow. DANSAT and MODFLOW were separately calibrated using the integrated GW approach which uses own lumped baseflow components in DANSAT, and using the steady-state mode in MODFLOW, respectively. Then the linked system was applied to QN2 based on the parameters selected for DANSAT and MODFLOW to simulate time-dependent interactions on the entire system. The linked approach was better than the integrated approach for predicting the temporal trends of monthly runoff by improving the monthly Nash–Sutcliffe efficiency index from 0.53 to 0.60. The proposed linked approach will be useful for evaluating the impacts of agricultural BMPs on the entire SW–GW system by providing spatial distribution and temporal changes in groundwater table elevation and enhancing the reliability of calibrated parameter sets.

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1. Introduction

Non-point source (NPS) pollution from both urban and agricultural sources is the most significant source of water quality problems in the United States (USEPA, 2000). Contaminations of subsurface soil and groundwater by NPS pollutants are serious, because the areal extent of contamination is significant and effective remediation is very difficult (Corwin and Wagenet, 1996). Results from the first set of groundwater/land use studies conducted in the National Water Quality Assessment (NAWQA) study indicated that pesticides were commonly detected in

shallow groundwater of both agricultural and urban areas (Kolpin et al., 1998). However, agricultural areas showed higher frequency of pesticide detection in groundwater than urban areas (Kolpin et al., 1998). Increased attention has been given to the contamination of groundwater because groundwater is a major source of drinking water in the U.S. (Van Den Berg and Van Den Linden, 1994). About 47% of the population in the U.S. obtained drinking water from groundwater (Hutson et al., 2004). Furthermore, continued contamination of surface water resources has increased dependence on groundwater to meet growing water needs. The interaction between surface water and groundwater in many perennial streams has a significant influence on chemical and biological conditions of both surface and subsurface systems. Therefore, investigation of the interaction of surface water and groundwater is important in order to determine the effects of land use changes on water resources. Best management practices

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(BMPs) have been used to reduce or eliminate the losses of pollutants from diffuse sources into receiving waters (Line et al., 1999). Selection of BMPs should take into consideration the BMP effect on both surface and groundwater. Some BMPs implemented for reducing surface water quality problems may accelerate pollutant transport to groundwater (Smith et al., 1991). For example, conservation tillage management, including no-till practice, has been used because of its affirmative impacts on reducing soil erosion and loss of related pollutants to surface waters. However, impacts of conservation tillage on groundwater quality are controversial. Several researchers have reported on negative aspects of no-till practice with increased pesticide leaching to groundwater (Barbash and Resek, 1995; Heatwole et al., 1997).

Modeling approach has been widely used for conjunctive investigation of surface water and groundwater. Existing groundwater models can be used for considering aquifer–stream interactions. A three-dimensional finite-difference groundwater flow model (MODFLOW; McDonald and Harbaugh, 1988) has been widely used in groundwater modeling studies. The river or streamflow routing package of MODFLOW considers a flow between groundwater and surface water systems. Swain (1994) developed a coupled surface water and groundwater flow model (MODBRANCH) for simulation of stream–aquifer interactions. The model links MODFLOW to a one-dimensional numerical model BRANCH (Schaffranek et al., 1981) which is designed to simulate unsteady flow in open-channel networks. In MODBRANCH, streams are simulated more realistically than in the river and streamflow routing packages of MODFLOW. Havard et al. (1995) linked a newly developed one-dimensional unsaturated flow model to MODFLOW for calculating the movement of water during various water table management practices. The linked model, LINKFLOW, was validated against observed data and the simulated results showed good agreement with measured values (Havard et al., 1997). Sophocleous et al. (1999) replaced the groundwater component of the soil and water assessment tool (SWAT) with MODFLOW in order to evaluate long-term water management strategies. Daily and monthly time steps were used for SWAT and MODFLOW simulation, respectively. A weighted average in SWAT was used as input to MODFLOW for each aquifer time step. The integrated model demonstrating two-way interactions between surface and groundwater was applied to three different watersheds in Kansas (Sophocleous and Perkins, 2000). Cho et al. (2009) evaluated the impact of land use activities on the surface and subsurface flow regimes by using the Hydrologic Simulation Program-Fortran (HSPF) simulation results as inputs to MODFLOW. Differences in spatial and temporal scales provided challenges when linking a lumped surface hydrology model with a distributed groundwater model. MIKE-SHE is one of the very few currently available integrated, physically based, and fully distributed modeling tools suitable for considering the interaction between surface water and groundwater. Jayatilaka et al. (1998) simulated hydrology in a small experimental irrigation site using MIKE-SHE to quantify the effects of flow processes on surface drainage and shallow groundwater level. Andersen et al. (2001) modified the MIKE-SHE model to simplify the movement of water in the subsurface zone. In this model, water movement in the unsaturated zone is estimated based upon gravity, and the soil profile is represented by a number of computational nodes in the vertical direction. Heng and Nikolaidis (1998) developed the Watershed Nutrient Transport and Transformation (NTT-Watershed) model to simulate water and nutrient transport at the watershed scale. This model is a physically based, distributed-parameter model which can be used for predicting the fate and transport of nitrogen in surface, unsaturated, and saturated zones. The NTT-Watershed model performed well in simulating hydrology

and nitrogen dynamics in the Muddy Brook watershed in Connecticut (Heng and Nikolaidis, 1998). Yu and Schwartz (1998) developed a physically based, distributed parameter model, Basin Scale Hydrologic Model (BSHM), to simulate hydrologic responses on a basin scale considering water movement in both surface and subsurface areas. The interaction between stream and groundwater is considered based on Darcy's equation with assumptions of rectangular channel geometry and a hydraulic conductivity of streambed that is smaller than the aquifer. However, none of these is appropriate for evaluating impacts of spatially and temporally changing agricultural BMPs on the entire water resource system including surface water and groundwater.

Dynamic Agricultural Non-point Source Assessment Tool (DANSAT) is the distributed-parameter, physically based, and continuous-simulation model for simulating spatial and temporal impacts of agricultural BMPs on hydrology and water quality in small agricultural watersheds (Cho, 2007; Cho and Mostaghimi, 2009a,b,c). The cell-based component of DANSAT, which is a prerequisite for watershed-scale evaluation of the impact of agricultural management practices on surface and groundwater, was applied to a field plot, located in the coastal plains of Virginia and movements of percolated water and pesticides in the root zone of the plot were well reproduced by the model. The impact of temporal and spatial changes in crop rotation on both surface and subsurface hydrology was evaluated by Cho and Mostaghimi (2009a) using DANSAT. Agricultural activities caused differences in the amount of infiltrated water and thus the recharge to groundwater and runoff in streams. However, the integrated GW components in DANSAT, which simulate movement of water and pollutant without considering the actual flow path within the saturated zone, have limitations in considering dynamic interactions between surface and subsurface regimes. The overall objective of this research is (1) to develop a modeling system for evaluating the effect of BMPs on both surface water and groundwater by considering dynamic interactions, and (2) to demonstrate the applicability of the developed system at a watershed scale.

2. Methods

2.1. Selecting a method to evaluate surface and groundwater interaction

An ideal modeling system should be able to simulate the impacts of land use changes on hydrology and water quality of surface and subsurface areas even though the selection of an appropriate approach for considering interactions between surface and groundwater depends on the acceptable assumptions and available data required for simulations. Possible approaches for considering the interactions between surface water and groundwater include: (1) use of existing groundwater models (stand alone approach), (2) linkage of groundwater model and surface hydrology model (linked approach), and (3) developing an integrated surface–subsurface model (integrated approach). Among the three possible approaches, the stand alone approach is not appropriate for this study because most of these models including MODFLOW do not consider the impacts of overland-applied BMPs on groundwater. The integrated approach can be more efficient than the linked model approach in terms of its application. The integrated approach can minimize the size of the model by incorporating only necessary algorithms or functions into the integrated model. The integrated approach uses computer memory to consider both the surface-to-groundwater and groundwater-to-stream interactions, rather than saving and retrieving a data file. As a result, the integrated approach may decrease the computation time and increase the efficiency of model applications. In addition, the integrated approach has the advantage of smaller

input data requirement, compared to the linked approach. However, integrated approach would require more developing time and be less reliable than a linked approach from the model developer's point of view because the integrated approach requires modification of most existing model components and verification of the newly developed components. In contrast to the integrated approach, the linked approach has the flexibility of exchanging a component of one model with an appropriate component from another model. SWAT component of SWATMOD can be substituted by another surface hydrology model, such as POTYLD, without modifying the original source code of SWAT, POTYLD, or MODFLOW (Koelliker, 1994). Developing a new interface module or modifying an existing interface module for a linked system is easier and more reliable than developing a new integrated surface-groundwater modeling system because individual models in a linked system have been widely used and are already verified. As a result, only a verification process for the interface module is necessary. However, the major disadvantage of the linked approach is in its input data requirement because some input data can be overlapped between individual surface and groundwater models. Users also need to be familiar with all individual models.

In this research, more importance was given to the flexibility and reliability rather than the efficiency of the model, considering the fast growth of computer hardware. As a result, the linked modeling approach was selected to consider the interaction between surface and groundwater. DANSAT was selected for predicting the movement of water in runoff and in leachate at a watershed scale while MODFLOW and a modular three-dimensional transport model (MT3D; Zheng, 1990) were selected as groundwater models for the linked approach for simulating water and pesticide movement in the saturated zone, respectively. Fig. 1 shows the conceptual model of the selected linked approach.

2.2. Modeling strategies to consider two-way interactions

The linked approach should have the ability to consider two-way interactions between surface and groundwater. Both interactive influences of surface water on groundwater (surface-to-aquifer interaction) and groundwater on surface water (aquifer-to-stream interaction) should be considered. Changes in the groundwater table resulting from recharge should be reflected in the groundwater simulation by changing the input data for the groundwater model. Similarly, the changes in calculated discharge from aquifer to the stream segment should be considered in the surface model simulation to consider interactions between the two systems.

The major difficulty in linking a surface water model with a groundwater model is derived from the differences in their temporal and spatial scales. If the surface and groundwater models use different spatial scales, the recharges and pesticide loads from surface water should be lumped or subdivided into the various

discrete cells of the groundwater model. Specifically, linkage between a lumped or semi-lumped surface model and a distributed groundwater model such as HSPF-MODFLOW or SWAT-MODFLOW has difficulties in taking into account the location of land use changes that could have significant impacts on streamflow and hydraulic head in groundwater (Cho et al., 2009; Sophocleous and Perkins, 2000). With regard to the spatial scale, smaller grid-size is recommended for the distributed parameter in the non-point source pollution (NPS) model to satisfy the assumption that all properties such as soil, vegetation, surface condition, crop management, and climate are homogeneous within each grid (Dillaha, 1990). Although a smaller grid size can be used for local groundwater simulation, larger grid sizes (>10 ha) are typically used in most watershed scale groundwater modeling. When a smaller grid size for the surface model and a larger grid size for the groundwater model are used, fluxes such as recharges and pollutant loads from several surface cells should be spatially lumped into the underlying groundwater cell. Using the same larger grid size of the groundwater model for both surface and groundwater models can violate the homogeneous assumption of the surface model. In this research, the same smaller grid size based on surface modeling is selected for both surface and groundwater models to avoid inefficiency at the expense of computational time.

The surface and groundwater models also operate on different time scales. The difference in time step is appropriate considering that surface runoff occurs more quickly than groundwater flow. DANSAT uses varying time steps from a minimum 1-min storm event time step during rainfall events to a daily time step between rainfall events (Cho and Mostaghimi, 2009b). A user can decide on the groundwater time step as an input parameter, which should be equal to or greater than surface water time step (Fig. 2). An appropriate time step for the groundwater model need to be decided based on the characteristic of groundwater flow. A shorter time step will be necessary if the groundwater table significantly fluctuate during a small period of time.

In this study, a Dual-simulation Approach (DSA) was developed to consider surface-to-aquifer and aquifer-to-stream interactions. Fig. 3 shows the flowchart of the DSA. DSA consists of three main procedures. First, Virtual Simulations (VS) predict the daily recharges and pesticide fluxes to the groundwater by assigning and using temporal arrays within DANSAT. The recharge input file of MODFLOW (*.rch) and the sink and source mixing input file of MT3D (*.ssm) are updated based on temporally calculated daily recharges and pesticide fluxes. Second, groundwater models are run at the transient mode using updated input data to predict the daily discharges from aquifer to stream segments. Third, Actual Simulation (AS) predicts the final results for hydrology, sediment, and pesticides considering the input from the groundwater models. The VS and AS use exact the same internal values for the simulations except for changes in flux from groundwater to

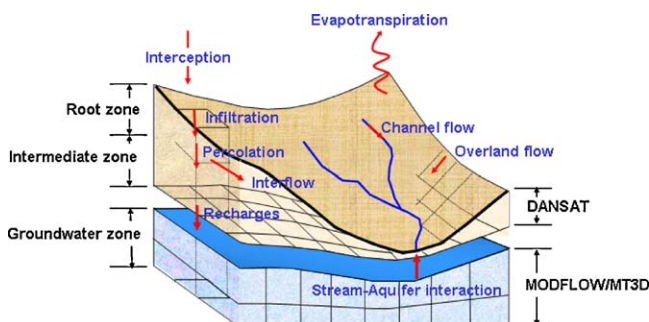


Fig. 1. Conceptual model of the linked approach.

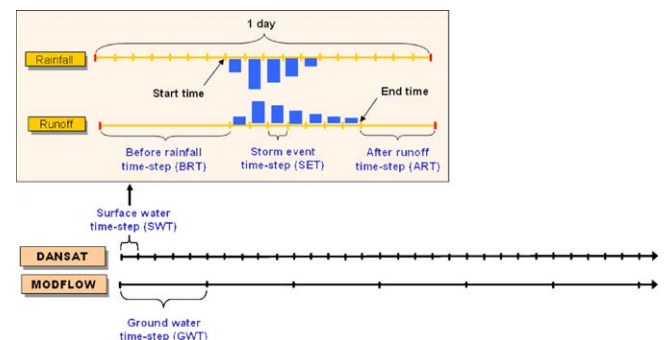


Fig. 2. Flowchart representation of time steps for various model components.

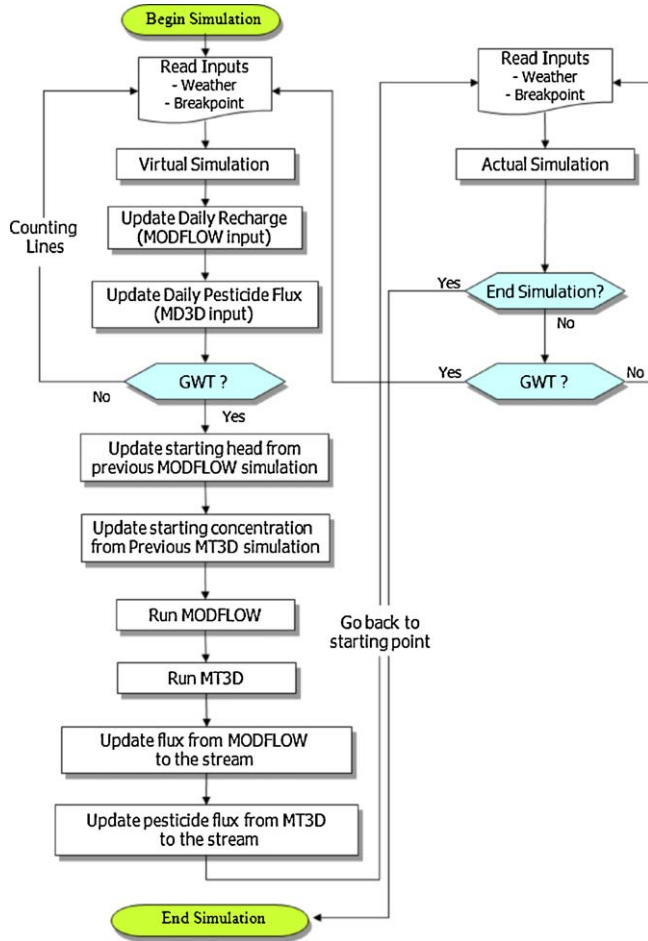


Fig. 3. Flowchart of the dual simulation approach (GWT is a user-defined groundwater time step).

stream. In representing the dynamic surface-to-aquifer interactions, daily recharge input option in the recharge module of MODFLOW was used to prevent the daily predicted recharge and pesticide loads in DANSAT from being lumped into the larger time step of MODFLOW.

2.3. Modeling steps and performance measures

The modeling procedure for the linked approach consists of three steps: (1) calibrating DANSAT based on the integrated baseflow components (integrated DANSAT simulation); (2) calibrating the groundwater models in a steady-state condition (steady-state GW simulation); (3) running the linked system at a transient mode based on the selected input parameters from the integrated DANSAT simulation and steady-state groundwater simulation to simulate a time dependent impact of land use activities on the hydraulic head and streamflow (linked SW/GW simulation).

The integrated DANSAT simulation uses own groundwater components of DANSAT for simulating baseflow based on spatially distributed recharge fluxes (Cho and Mostaghimi, 2009b). General procedures for preparing and calibrating parameters for DANSAT are described in previous studies by Cho and Mostaghimi (2009a). The study area was divided into 0.81 ha grid size (90 m × 90 m cell) and a 1-min storm event time step (SET) was selected.

MODFLOW was calibrated in a steady-state condition against the hydraulic head and streamflow rate. After calibrating the hydraulic conductivity of the unconfined layer, streambed con-

ductance was changed to match the observed and simulated streamflow rates. A trial-and-error method was employed to calibrate the model. A 10-day time-step for groundwater simulations was selected.

Linked SW/GW simulation uses existing groundwater models such as MODFLOW and MT3D instead of the integrated baseflow components in DANSAT. The same DANSAT input files developed for the integrated DANSAT simulation was used for the linked application except for changes in groundwater components. Boundary and initial conditions constructed based on the steady-state GW simulation were used for the application of the linked system in a transient mode. Multiple criteria based on different time scales, including simulation total, and monthly and daily statistics were selected for evaluating the performance of the integrated groundwater approach. Percent error (PE) was selected as a general quantitative measure for the comparison of observed and simulated outputs for the entire simulation period. Normalized objective function (NOF) (Pennell et al., 1990) and Nash–Sutcliffe efficiency index (NSE) (Nash and Sutcliffe, 1970) were selected as error statistics and correlation related statistics for the daily and monthly output, respectively. The measures used in this research were calculated using the following relationships:

$$PE = \left(\frac{P_{\text{tot}} - O_{\text{tot}}}{O_{\text{tot}}} \right) \times 100 \quad (1)$$

$$MAE = \frac{\sum_{i=1}^t |O_i - P_i|}{t} \quad (2)$$

$$NOF = \frac{RMSE}{\bar{O}} = \frac{\sqrt{(1/t) \sum_{i=1}^t (O_i - P_i)^2}}{\bar{O}} \quad (3)$$

$$NSE = 1 - \frac{\sum_{i=1}^t (O_i - P_i)^2}{\sum_{i=1}^t (O_i - \bar{O})^2} \quad (4)$$

where PE is the percentage error of a prediction (%), P_{tot} is the simulated total for the entire simulation period, O_{tot} is the observed total for the entire simulation period, MAE is the mean absolute error, NOF is the normalized objective function, RMSE is the root mean square error, NSE is the Nash–Sutcliffe efficiency index, O_i is observed value of an event i , P_i is predicted value of an event i , t is number of observed values and \bar{O} is average observed value.

3. Materials

3.1. Study area

QN2 subwatershed in the Nomini Creek (NC) watershed, which is the same watershed used for the integrated DANSAT application by Cho and Mostaghimi (2009a), was selected for validating the developed interface components for the surface and groundwater interaction by linkage DANSAT to existing groundwater models such as MODFLOW and MT3D. The NC watershed is agricultural, with 49% cropland, 47% woodland, and 4% residential and roads. Corn, soybeans, and small grains are the major crops in the watershed. Suffolk and Rumford series, which cover about 90% of the watershed by a sandy loam texture, are the major soils in the NC watershed. Both soils are deep and well drained. The NC watershed is an ideal watershed for evaluating baseflow related components because over 85% of the total runoff in the watershed is due to groundwater discharge. Four paired wells were installed to a depth ranging from 10 to 17 m in order to assess the underlying groundwater hydrology and quality. Fig. 4 shows the location of groundwater monitoring wells in the NC watershed.

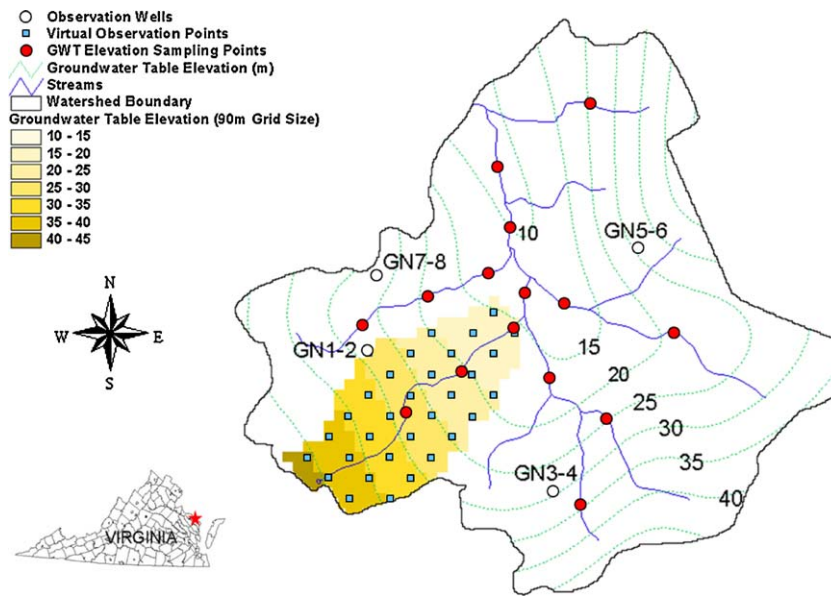


Fig. 4. Location of groundwater monitoring wells in the Nomini Creek watershed.

Detailed information on the watershed is provided by Mostaghimi et al. (1989, 1999).

3.2. Development of input parameters

Only detail procedures for the groundwater modeling will be described in this section because the procedures for the integrated DANSAT application was described in detail by Cho and Mostaghimi (2009a) and the accuracy of the linked GW simulation depends on how reasonably the saturated area is simulated by the groundwater models. The pesticide components were not simulated in the linked approach due to lack of parameter information for the MT3D simulation, even though the code for the linked SW/GW simulation for pesticide components (interface code for the interaction between DANSAT and MT3D) was incorporated. Available information and data were compiled for the study area to develop the conceptual model for the MODFLOW simulations.

3.2.1. Average groundwater table elevation

Generation of reliable distribution of average groundwater table (GWT) elevation is important for the steady-state groundwater simulation. Spatial distribution of average groundwater table cannot be generated with only one pair of groundwater monitoring station (GN1–2) inside the QN2 (Fig. 4). Sixteen points were sampled in streams to obtain approximate elevation of groundwater table throughout the NC watershed. It is assumed that the groundwater table is connected with the streambed considering that over 85% of the total runoff came from groundwater in QN2. Fig. 4 shows the location of groundwater monitoring stations (midpoints of paired monitoring wells), selected stream points for interpolating groundwater table (red points), and generated contours of average groundwater table. Multiple observation wells are required inside the watershed in order to calculate simulation error after the calibration of the groundwater model. Virtual observation wells were defined throughout the watershed because only one pair of groundwater monitoring well was available in QN2 (Fig. 4). Observed hydraulic head information for virtual observation wells was generated based on interpolated average groundwater table elevation. A constant head boundary was added near the watershed outlet by considering the fact that contour lines of groundwater table elevation are parallel to the watershed boundary of QN2 near the watershed outlet areas.

3.2.2. Model layer

Only one layer of saturated zone was considered in the groundwater simulations with MODFLOW because the average GWT elevation at eight monitoring stations (GN1–8) is about 10 m below the ground surface according to the 10 years of observed data (Mostaghimi et al., 1999). This layer represents the unconfined aquifer. The bedrock was not considered because QN2 is not big enough to consider deep groundwater movement. Surface elevation was created using a digital elevation model (DEM) for representing the land surface of the conceptual model. The bottom boundary of the layer was assumed to be 5 m from the sea level. Hydraulic conductivity in a shallow unconfined aquifer can vary depending on the different soil types. However, one homogeneous hydraulic conductivity value was assigned for the unconfined layer because no significant spatial distribution of the hydrologic soil group, which indicates the minimum rate of infiltration obtained for base soil after prolonged wetting, was detected in QN2. Hydrologic soil group B with moderated infiltration rate covers 96% of the watershed and hydrologic soil group D with very low infiltration rate exists near the streams, covering 3.4% of the watershed. The spatial distribution of hydrologic soil group D near streams can be considered by changing the streambed conductivity parameters.

3.2.3. Average recharge

The recharge package of MODFLOW was used to simulate the hydrologic impact of agricultural BMPs on the groundwater system. To consider spatial distribution of daily average recharges into the saturated zone, the approximate total recharge value throughout the watershed needs to be calculated. The average annual recharge value was calculated based on the observed daily baseflow data during the 4 years of simulation (1987–1990). Daily baseflow was estimated based on daily total runoff using the baseflow separation filter which is provided in the SWAT model (Arnold et al., 1995) and the average annual recharge value was calculated based on estimated total baseflow. Then, the average annual recharge amount was distributed to the six land use types based on the degree of perviousness for each land use type. Fig. 5 shows the spatial distribution of land use categories in QN2. Perviousness of 100% was assumed for crop, forest, hay, and pasture areas while 80 and 60% perviousness were assumed for low and high density developed areas, respectively (Table 1).



Fig. 5. Spatial distribution of land use categories in the QN2 subwatershed.

Table 1
Perviousness, and annual average recharge value for each land use type.

Land use activity	Crop	Hay	Pasture	Forest	LDR	HDR
Degree of perviousness (%)	100	100	100	100	80	60
Land use percent (%)	33	2	4	59	0.4	2
Average annual recharge (mm/day)	1.052	1.052	1.052	1.052	0.841	0.631

Distribution of average annual recharge to land use types was made under the assumption that recharge values are related to the land use activities. For example, the recharge in urban areas would be smaller than the recharge occurring in relatively pervious agricultural areas. However, possible difference in recharges among agricultural and forest areas mainly due to difference in evapotranspiration was not considered because of lack of measured information.

3.2.4. Stream input

The Streamflow Routing package of MODFLOW was selected to represent the stream in this study. Due to the difficulty in measuring streambed conductance values, input parameters were determined through calibration. Observed average streamflow rates for the model calibration were calculated based on the observed daily runoff data at the QN2 watershed outlet. Total baseflow, estimated using the baseflow separation filter, was used to calculate average streamflow rate which needs to be compared with the simulated total flux between aquifer and streams.

4. Results and discussion

4.1. Steady-state calibration of MODFLOW

Table 2 shows a summary of the steady-state calibration results for both hydraulic head and streamflow rate. The mean error for the hydraulic head was 3.07 m based on 33 observation points. According to the spatial distribution of average GWT elevation in Fig. 4, maximum values occurred near the headwater of the watershed and minimum hydraulic head occurred near the watershed outlet. The simulated and observed minimum values of the hydraulic head are close to each other with 15.7 and 15.2 m, respectively. The median value of the simulation results was greater than that of observed values while the simulated maximum value was smaller. Fig. 6 shows the scatter-plot of observed and simulated hydraulic head at monitoring wells described in Fig. 4. According to the error statistics in Table 2,

Table 2

Results of steady-state calibration of MODFLOW for the QN2 subwatershed.

Component	Criteria	Observed	Simulated	Errors
Hydraulic head	Min head (m)	15.7	15.2	
	Max head (m)	42.5	40.7	
	Median head (m)	27.9	31.8	
	Mean error (m)			3.07
	Mean abs error (m)			3.30
	Root mean sq. error (m)			3.66
Streamflow	Flow rate (m ³ /day)	2257	2097	
	Percent error (%)			−7.1

the model closely reproduced the trend in groundwater table elevations both near the watershed outlet and in the headwater of the watershed. However, most of overprediction occurred near the middle area of the watershed. As mentioned previously, the hydraulic head information at each virtual observation well was generated based on interpolated average groundwater table elevation. Only one point, GN1–2, has a measured value which is an average groundwater table elevation based on GN1 and GN2. The observed hydraulic head at GN1–2 was 28.47 m compared with the simulated hydraulic head of 31.78 m. Results indicate that the steady-state model reasonably reproduces the spatial distribution of the hydraulic head throughout the watershed. In the case of stream fluxes, the error was −7.1% for the observed and simulated flow rates of 2257 and 2097 m³/day, respectively. These data also illustrate the performance of the model and shows that the model does a relatively good job of matching the observed hydraulic head elevation and streamflow rates.

4.2. Transient simulation of linked approach

Comparison of observed and simulated annual total runoff by the linked and integrated GW approaches at QN2, along with the summary of model performance statistics, are shown in Table 3. Cumulative total runoff volume was well predicted with −7.09% error. Total runoff by the linked approach during the simulation period was decreased to 1714 mm compared to 1833 mm by integrated approach. Monthly mean absolute error (MAE) and root mean square error (RMSE) were respectively improved to 4.10 and 5.74 mm in the linked approach compared to 4.97 and 6.23 mm in the integrated. Daily NOF values for the two different approaches

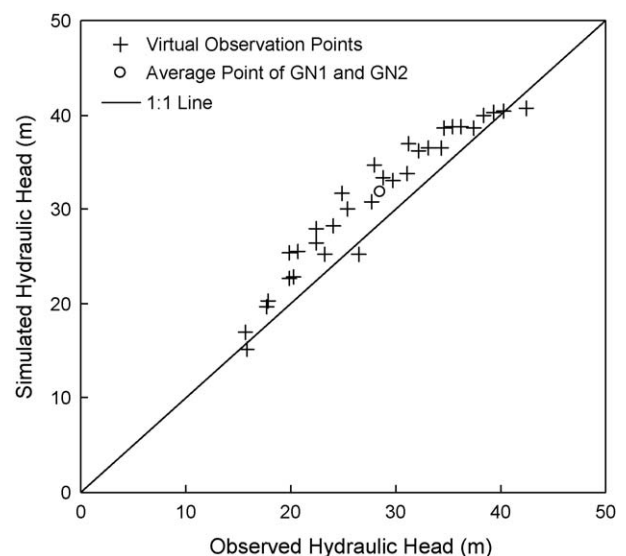


Fig. 6. Observed and simulated hydraulic heads at the monitoring wells of QN2.

Table 3

Comparison of observed and simulated annual total runoff by the linked GW approach for the calibration period at QN2, along with the summary of model performance criteria.

	Runoff	
	Observed	Simulated
Year		
1987	425	403 (358)
1988	356	350 (323)
1989	479	489 (578)
1990	586	472 (574)
Total	1846	1714 (1833)
Percent error (%)		−7.09 (−0.64)
Monthly RMSE (mm)		5.74 (6.23)
Monthly MAE (mm)		4.10 (4.97)
Monthly NOF (mm)		0.15 (0.16)
Monthly NSE		0.60 (0.53)
Daily NOF (mm)		0.33 (0.33)
Daily NSE		0.60 (0.59)

(): summary from integrated GW approach.

RMSE: root mean square error (mm).

MAE: mean absolute error (mm).

NOF: normalized objective function (mm).

NSE: Nash–Sutcliffe model efficiency.

were the same while the daily NSE was slightly higher in the linked approach. However, the monthly NSE value by the linked approach was much higher (0.60) compared to the value of 0.53 by the integrated approach. Monthly NOF also decreased with similar values for both approaches (0.16 for the linked approach and 0.15 for the integrated approach). Fig. 7 shows temporal comparison of observed and simulated monthly runoff by the integrated and linked GW approaches. In the integrated GW approach, monthly runoffs were underestimated during 1987 and 1988, overestimated during 1989, and were close to the observed values during 1990. However, monthly runoff by the linked approach was closely reproduced from the beginning of the simulation to October 1989, and was underestimated during the remaining period.

The monthly NSE value in the linked SW/GW simulation can be improved from 0.6 to 0.73 by increasing the baseflow using a different parameter set from the integrated DANSAT simulation. Increase in baseflow can be simulated by increase in total porosity and decreased in field capacity because hydrology components of DANSAT in both surface and subsurface are sensitive to soil related parameters such as total porosity and field capacity (Cho and Mostaghimi, 2009a). However, the same input parameters for DANSAT were used for both integrated and linked simulations for comparison purpose.

The linked approach was better for predicting the temporal trends of monthly runoff than the integrated approach. The linked GW approach has several advantages compared to the integrated approach in spite of the fact that it requires much longer

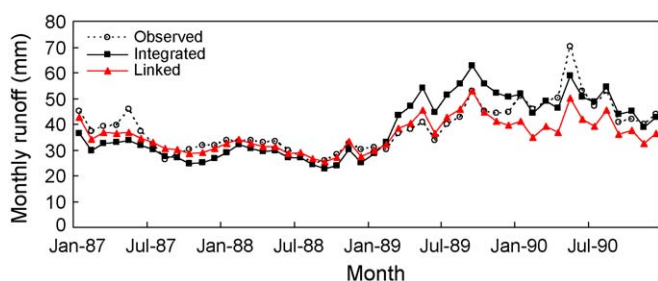


Fig. 7. Time series comparison of observed and simulated monthly runoff for both the integrated and linked GW approaches.

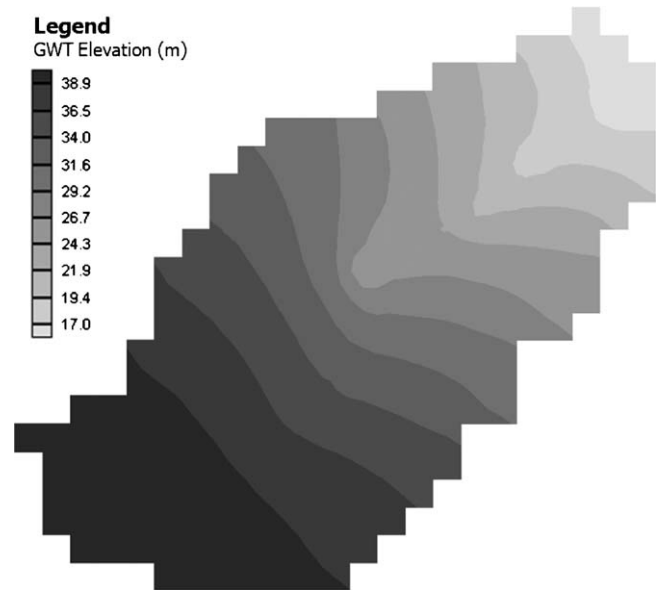


Fig. 8. Spatial distribution of the groundwater table (GWT) elevation at the end of the simulation period.

calculation time and more input parameters for the calibration of groundwater models. The major advantage of the linked system is that the linked approach is able to provide the spatial distribution and temporal changes in GWT elevation or pesticide concentration in groundwater. Fig. 8 shows the spatial distribution of GWT elevation predicted by MODFLOW at the end of simulation period. For the linked approach, the performance can be evaluated using observed data from the surface and saturated zone. For example, both runoff discharges at watershed outlets and spatial distribution of groundwater table elevation can be used for the validation of the model. The increased calibration target from both surface and groundwater enhances the reliability of the model results.

Compared to the integrated modeling approach by Cho and Mostaghimi (2009a) which showed the spatial distribution of difference in average monthly recharge for the two different crop rotation approaches, the linked modeling approach is recommended when the major concern in a watershed is to evaluate the impacts of agricultural BMPs on spatial distribution and temporal changes in GWT elevation or pesticide concentration in groundwater.

5. Summary and conclusions

The linked approach was selected and applied for 4 years (1987–1992) to demonstrate the applicability of the developed modeling system in evaluating hydrologic interactions between surface water and groundwater. The Dual-simulation (DS) approach was introduced to resolve the problems occurring by different temporal scales between DANSAT and MODFLOW/MT3D. The DANSAT–MODFLOW linked approach was applied to an agricultural watershed in Virginia. Only runoff was simulated using the linked approach due to lack of observed pesticide data for the groundwater model, MT3D.

Groundwater model, MODFLOW, was calibrated against both hydraulic head and streamflow rate using the steady-state simulation. Steady-state simulation results illustrated that MODFLOW reasonably reproduced the spatial distribution of the hydraulic head and streamflow rates throughout the watershed. Results from the integrated and linked approaches were compared with the observed data. The linked approach improved the

seasonal trend of baseflow prediction compared to the integrated approach by improving the monthly Nash–Sutcliffe efficiency index (NSE) from 0.53 to 0.60.

The advantage of the linked approach was demonstrated by displaying the spatial distribution of groundwater table elevation at the end of the simulation period. The integrated modeling approach that considers the interaction between surface water and groundwater enhances the reliability of the model results compared to individual surface and groundwater modeling approaches. The proposed linked approach will be helpful for the watershed manager to evaluate the impacts of agricultural BMPs on the entire system by considering surface water and groundwater interactions.

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